

EFFECTS OF ENVIRONMENTAL FACTORS ON ODOR EMISSION FROM PIG MANURE

P. D. Le, A. J. A. Aarnink, N. W. M. Ogink, M. W. A. Verstegen

ABSTRACT. *Altering environmental factors may change odor emission from pig manure. The main objective of this laboratory-scale study was to examine the effects of temperature, ventilation rate, emitting area, and manure dilution ratio on odor emission from growing pig manure, while also testing their effects on manure characteristics. Manure was placed in vessels with different surfaces (303, 475, and 595 cm²), and water was added to create different dilution ratios (0%, 50%, and 100%). The vessels were connected to glass capillaries with different ventilation rates through the headspace (0.5, 1.0, and 1.5 L min⁻¹) and were placed in climate-controlled rooms with different temperatures (10°C, 20°C, and 30°C). We used a face-centered central composite design with 54 experimental units in two rounds of three blocks. Odor samples were taken at the end of experiment (after seven days). Manure samples were collected at the start and at the end of the experiment. The mean odor emission from the manure vessel was 2326 ou_E h⁻¹ m⁻². Increased temperature, ventilation rate, and dilution ratio increased odor emission. Emitting area did not influence odor emission, but positively influenced total-N loss. Total-N loss increased as temperature and ventilation rate increased, but decreased as dilution ratio increased. Lowering temperature and ventilation rate can be considered as starting points to reduce odor emission from pig manure in practical conditions. The effects of dilution ratio and emitting area on odor emission could not be fully separated from the effect of headspace volume in this study and should be further studied.*

Keywords. *Environmental factors, Manure, Odor emission, Pigs.*

The odor formed and emitted from intensive pig production systems can be a serious nuisance to people living in the vicinity of pig farms and has been related to health problems by some authors (Donham, 2000; Iverson et al., 2000; Schenker et al., 1991; Schenker et al., 1998). In addition, some authors reported that some odorous compounds can affect both health and production efficiency of the animal (Boer et al., 1991; Tamminga, 1992). Within pig production, growing pigs are the main source of odor. Odor mainly comes from manure (Mackie et al., 1998). As a result, studies on odor from growing pig manure should receive high priority.

Odor is mainly formed from microbial conversion of organic compounds in manure. Odor is emitted into the air from buildings or external manure storage sites. Environmental factors, e.g., temperature, ventilation rate, dilution ratio, and emitting area, may influence the odor generation and emission process. Generally, the formation of most

odorous compounds increases at higher temperatures. High temperatures stimulate the formation of ammonia (Brunsch, 1997), hydrogen sulfide (Ni et al., 2000), 4-methyl phenol (p-cresol), and 3-methyl indole (skatole) (Spoelstra, 1976) in manure. Ventilation rate seems to be important as well, and is required in determining odor emission (Zhu et al., 2000). According to Oldenburg (1989) and Verdoes and Ogink (1997), there is a positive relationship between odor emission from pig houses and ventilation rate. Guingand et al. (1997) reported a 29% reduction in odor emissions from a growing-finishing pig house as the ventilation rate was reduced by 50%. According to Mol and Ogink (2003) and Ogink and Groot Koerkamp (2001), reducing the emitting area of the manure pit can reduce odor emission in pig houses. Dilution of manure is thought to have an effect on odor formation and emission because water is a solvent for bacterial conversions. In this solvent, odorous compounds are produced and broken down. However, we could not find any data in the literature on the effect of dilution on odor formation and emission.

The literature contains very little quantitative information on the effects of environmental factors in controlled conditions on odor concentration and emission from manure as measured by olfactometry. Furthermore, existing information on the effects of temperature and ventilation rate on odor emission in practice are difficult to interpret because these factors are generally confounded with each other and with other variables, e.g., pig weight. In addition, the effects of the interactions of different environmental factors on odor concentration and emission have not received much attention in previous studies. Altering and controlling environmental factors might reduce odor concentration and emission from pig manure. The objective of this study was to quantify the effects of temperature, ventilation rate, emitting area,

Article was submitted for review in June 2004; approved for publication by the Structures & Environment Division of ASAE in March 2005.

The authors are **Phung D. Le**, Researcher, Livestock Environment Department, Wageningen UR, Wageningen, The Netherlands, and Researcher, Faculty of Animal Sciences, Hue University of Agriculture and Forestry, Hue, Vietnam; **André J. A. Aarnink**, Scientific Researcher, Livestock Environment Department, Wageningen UR, Wageningen, The Netherlands; and **Nico W. M. Ogink**, Head of Livestock Environment Department, Wageningen UR, Wageningen, The Netherlands; and **Martin W. A. Verstegen**, Professor, Wageningen Institute of Animal Sciences (WIAS), Wageningen UR, Wageningen, The Netherlands. **Corresponding author:** A. J. A. Aarnink, Livestock Environment Department, Building No. 118, Wageningen UR, Bornsesteeg 59 6708 PD, Wageningen, The Netherlands; phone: +31-0-317-476554; fax: +31-0-317-425670; e-mail: andre.aarnink@wur.nl.

dilution ratio, and their interactions on odor concentration and emission from growing pig manure in combination with quantifying their effects on manure characteristics.

MATERIALS AND METHODS

Controlled lab experiments were conducted to determine how odor concentration and emission from manure and manure characteristics were affected by different environmental factors: temperature, ventilation rate, manure dilution ratio, and emitting area. The study used a laboratory setup with manure vessels whose headspace was ventilated by fresh air. The fresh air came from inside the climate-controlled room. The air in the climate-controlled room came from outside.

Independent factors included:

- Temperature (T) of the manure and air was set at three levels: 10°C, 20°C, and 30°C. One of these temperatures was maintained in each of three climate-controlled rooms.
- Ventilation rate of the manure vessels (V) was set at three levels: 0.5, 1.0, and 1.5 L min⁻¹. It was controlled by critical glass capillaries.
- Emitting area (E) was set at three levels: 303, 475, and 595 cm². Emitting area was controlled by vessels having different areas.
- Manure dilution rate (D) was set at three levels: 0%, 50%, and 100% (w/w). Manure was diluted with 0%, 50%, and 100% water.

Dependent factors included:

- Odor concentration and odor emission from the manure vessels.
- Manure characteristics, which included pH, dry matter, ash, total-N, NH₄⁺-N, total-N loss, and individual volatile fatty acids: acetic, propanoic, butanoic, pentanoic, iso-butanoic, iso-pentanoic, and total volatile fatty acids (VFAs).

EXPERIMENTAL DESIGN

A face-centered central composite design with blocks was used, according to the scheme of Cochran and Cox (1966). The experiment had three blocks. Each block had nine treatment combinations (table 1). Block was the effect of day. Within each block, the nine treatment combinations were started on the same day. We replicated the entire experiment once.

Figure 1 is a schematic of the laboratory setup for the experiment. Vessels were placed in climate-controlled rooms. There were nine manure vessels per room. Manure was placed in the vessel and kept under experimental conditions for seven days. Each vessel was closed with a lid, with a rubber gasket between the lid and the wall of the vessel to make the vessel airtight. Air entered the vessel via 24 holes of 1 mm diameter, located at the edge of the lid. Air was exhausted from the vessel by a hole of 5 mm diameter in the middle of the lid. From a previous test (unpublished results), we visually found that there was no direct shortcut from the incoming air to the outgoing air in the vessel. Air entering the vessel was from the climate-controlled room. Air entering the room was outside air. The incoming air in the vessels had the same absolute amount of water vapor (8.42 g m⁻³); therefore, relative humidities in the climate-controlled

Table 1. Design of the experiment.

| Block | Dilution (%) | Emitting Area (cm ²) | Temperature (°C) | Ventilation Rate (L min ⁻¹) |
|-------|--------------|----------------------------------|------------------|---|
| I | 0 | 303 | 10 | 0.5 |
| | 100 | 303 | 10 | 1.5 |
| | 0 | 595 | 10 | 1.5 |
| | 100 | 595 | 10 | 0.5 |
| | 0 | 303 | 30 | 1.5 |
| | 100 | 303 | 30 | 0.5 |
| | 0 | 595 | 30 | 0.5 |
| | 100 | 595 | 30 | 1.5 |
| | 50 | 475 | 20 | 1 |
| II | 0 | 303 | 10 | 1.5 |
| | 100 | 303 | 10 | 0.5 |
| | 0 | 595 | 10 | 0.5 |
| | 100 | 595 | 10 | 1.5 |
| | 0 | 303 | 30 | 0.5 |
| | 100 | 303 | 30 | 1.5 |
| | 0 | 595 | 30 | 1.5 |
| | 100 | 595 | 30 | 0.5 |
| | 50 | 475 | 20 | 1 |
| III | 0 | 475 | 20 | 1 |
| | 100 | 475 | 20 | 1 |
| | 50 | 303 | 20 | 1 |
| | 50 | 595 | 20 | 1 |
| | 50 | 475 | 10 | 1 |
| | 50 | 475 | 30 | 1 |
| | 50 | 475 | 20 | 0.5 |
| | 50 | 475 | 20 | 1.5 |
| | 50 | 475 | 20 | 1 |

rooms were 90%, 49%, and 28% in the 10°C, 20°C, and 30°C rooms, respectively.

The ventilation rate was controlled by critical glass capillaries connected to vacuum pumps that pulled the air from the vessels. The outgoing air from the vessels was released outside (fig. 1). Odor samples were always collected at a flow rate of 0.5 L min⁻¹, while the vessel ventilating rate remained constant during sampling. At the ventilation rate of 0.5 L min⁻¹, a 0.5 L min⁻¹ critical glass capillary was used. At the ventilation rate of 1.0 L min⁻¹, two 0.5 L min⁻¹ critical glass capillaries were used, and at the ventilation rate of 1.5 L min⁻¹, one 0.5 L min⁻¹, and one 1.0 L min⁻¹ critical glass capillaries were used.

As mentioned above, the vessels had different surfaces (303, 475, and 595 cm²) but the same height (23.5 cm), so

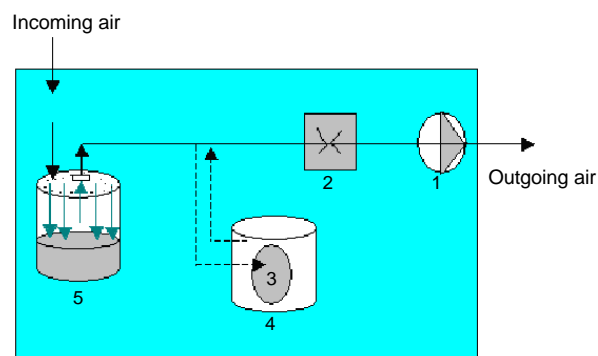


Figure 1. Schematic view of the laboratory setup of the experiment in a climate-controlled room: 1 = pump, 2 = critical glass capillary, 3 = sample bag, 4 = container, and 5 = manure vessel.

they had different volumes. Net vessel volumes for the three surfaces were 7116, 11164, and 13991 cm³, respectively. A blank vessel (without manure but with the same amount of clean water) was placed in each climate-controlled room to investigate the background odor concentration, or the odor concentration of the incoming air. The laboratory setup of the blank vessel was exactly the same as that of the manure vessels.

MANURE AND PIGS

Manure was taken from a deep pit below a barn where pigs from 25 to 50 kg were kept. The pigs were housed in partially slatted floor pens. They were fed *ad libitum* a typical commercial diet with 170 g CP, 46.62 g crude fiber, and 9.9 MJ NE per kg of feed. The manure was released at a high velocity to a temporary storage container. The manure was mixed in the temporary storage container before sampling. A total of 200 kg of manure was collected. The manure pit had not been emptied for two months prior to manure collection.

The collected manure was mixed for 5 min and divided it into two parts. One part was used in the first round of the experiment, and the other part was used in the second round. The manure for the second round was stored in a room at 4°C for nine days until it was used. The manure was mixed again for 5 min before each vessel was filled with 2.0 kg of manure. Water was added to each vessel to dilute the manure to either 50% or 100%. Finally, all vessels were stored in a room at 4°C for one to three days depending on the assigned day (block) in the experimental system.

SAMPLES AND SAMPLING

Two kinds of samples were taken: manure samples and odor samples.

Manure Samples

Manure samples were taken at the beginning and end of the experiment. At the beginning of each round of the experiment, at the same time that manure was put into vessels, we took a duplicate sample. At the end of the experiment, after odor samples were collected, the manure in each vessel was mixed for 1 min, and a 1 kg manure sample was then taken from each vessel.

Odor Samples

After running the experiment for seven days, we collected odor samples from the air leaving the vessels. The sampling method for delayed olfactometry using the “lung principle” was used. A 40 L Nalophaan odor sampling bag was placed in a rigid container (fig. 1). The sample bag had been flushed with compressed and odorless air three times before it was placed in a rigid container for collection of the odor sample. The sample bag was used only once for one odor sample, as recommended by CEN Standard 13725 (CEN, 2003). The air was removed from the container using a vacuum pump, and the vacuum in the container caused the bag to fill with a volume of sample equal to the volume removed from the container. The flow rate of air entering the sample bag was 0.5 L min⁻¹.

The experimental system kept running while the odor sample was collected, and the total ventilating rate was not changed during sampling. One odor sample was taken from each manure vessel. At the same time, an air sample was taken from the blank vessel in each climate-controlled room.

During transport and storage, odor samples were kept at a temperature above the dewpoint of the sample to avoid condensation. This was achieved by warming the rigid container of the odor bag. The interval between sampling and measuring the odor concentration did not exceed 24 h. This procedure was recommended by CEN Standard 13725 (CEN, 2003).

SAMPLE ANALYSES AND CALCULATIONS

Manure Samples

All manure samples were analyzed in duplicate. Dry matter, ash, and total-N were analyzed according to AOAC methods (AOAC, 1990), and NH₄⁺-N was determined spectrophotometrically according to NEN Standard 6472 (NEN, 1983). Volatile fatty acids, e.g., acetic, propanoic, butanoic, pentanoic, iso-butanoic, and iso-pentanoic, were measured using a Packard 427 gas chromatograph equipped with a flame ionization detector (Derikx et al., 1994).

The concentrations of each VFA, total VFAs, total-N, NH₄⁺-N, and dry matter were calculated per kg of manure and per kg of ash. Total-N loss was calculated by subtracting total-N in the manure after the experiment from that before the experiment. The weight of manure after the experiment was calculated with equation 1:

$$W_E = \frac{Ash_B \cdot W_B}{Ash_E} \quad (1)$$

where

W_E = weight of manure after the experiment (kg)

W_B = weight of manure before the experiment (2.0 kg)

Ash_B = ash concentration before the experiment (g/kg)

Ash_E = ash concentration after the experiment (g/kg).

Odor Samples

The European standard (CEN, 2003) was used to measure odor concentration by olfactometry. Odor concentration of the examined sample was expressed in European odor units per cubic meter air (ou_E m⁻³). One odor unit is defined as the amount of odor-causing gases that, when diluted in 1 m³ of air, can just be distinguished from clean air by 50% of the members of an odor panel. Six qualified panelists, who were screened to determine their odor sensing ability (20 to 80 ppb n-butanol), provided their responses to two sniffing tubes of a dynamic dilution olfactometer. The odorous and odorless air was randomly presented in one of the two sniffing tubes. At each presentation, each panelist indicated via an electronic keyboard which sniffing tube released the odorous air. They declared whether their selection was “guess,” “not certain,” and “certain.” A range of at least six dilution steps, each differing from the next by a factor of 2, was presented to the panelists in ascending concentration. Initial sample presentations were below the panelist detection threshold. Odor concentrations were increased until all panelists in two consecutive steps certainly indicated the correct sniffing tube with odorous air. The entire range of dilution steps was repeated three times.

From the indication of each individual panelist, odor concentration was calculated in three steps:

1. Calculating the individual detection threshold: the geometric mean of the last non-detectable (guess or not certain) dilution ratio and the first certain detectable dilution ratio.

2. Calculating the panel detection threshold: the geometric mean of the individual detection thresholds of all panelists.
3. Retrospective screening of each panelist threshold: CEN Standard 13725 (CEN, 2003).

Steps 2 and 3 were repeated until there were no outlying individual results; the odor concentration reported is the geometric mean of the individual detection thresholds of the panelists.

Because the incoming air may be odorous, the difference in odor concentration between the outgoing and incoming air should be used to calculate the net odor concentration (Miller et al., 2000; Smith and Dalton, 1999). Net odor concentration ($ou_E m^{-3}$) of the manure in the vessel was calculated as the difference between the odor concentration of the odor sample from the manure vessel and that of the blank vessel.

Net odor emission per time unit was defined as the number of odor units emitted from the manure vessel (after correcting for that of the blank sample) per time unit. It was calculated by multiplying the ventilation rate with the corresponding net odor concentration:

$$E_t = C_{odor} \frac{V}{1000} 60 \quad (2)$$

where

E_t = odor emission per hour ($ou_E h^{-1}$)

C_{odor} = odor concentration ($ou_E m^{-3}$)

V = ventilation rate ($L min^{-1}$)

60 = 60 min h^{-1}

1,000 = 1,000 L m^{-3} .

Net odor emission per surface unit was defined as the number of odor units emitted from the manure vessel per hour per surface unit. It was calculated with equation 3:

$$E_{t,a} = \frac{C_{odor} \cdot V \cdot 60 \cdot 10,000}{E \cdot 1,000} \quad (3)$$

where

$E_{t,a}$ = odor emission per hour per square meter manure area ($ou_E h^{-1} m^{-2}$)

E = emitting area (cm^2)

C_{odor} = odor concentration ($ou_E m^{-3}$)

V = ventilation rate ($L min^{-1}$)

60 = 60 min h^{-1}

1,000 = 1,000 L m^{-3}

10,000 = 10,000 $cm^2 m^{-2}$.

Equation 3 can be abbreviated as in equation 4.

$$E_{t,a} = \frac{C_{odor} \cdot V \cdot 600}{E} \quad (4)$$

Gross odor concentration and odor emission were defined as the concentrations and emission of the exhaust air only (not subtracting the contribution of inlet odors).

DATA ANALYSIS

We used the Genstat statistical package, 7th edition (Genstat, 2004), to analyze the effect of environmental factors on odor concentration and emission and manure characteristics. The following model was used:

$$Y = \beta_0 + R_i + B_j + \beta_1 T + \beta_2 V + \beta_3 E + \beta_4 D + \beta_5 TV + \beta_6 TD + \beta_7 TE + \beta_8 VD + \beta_9 VE + \beta_{10} ED + error \quad (5)$$

where

Y = dependent factors (odor concentration, odor emission, and manure characteristics)

β_0 to β_{10} = regression coefficients

R_i = effect of round ($i = 1$ to 2)

B_j = effect of block (the day starting the experiment with certain manure vessels, $j = 1$ to 3)

T = effect of temperature ($^{\circ}C$)

V = effect of ventilation ($L min^{-1}$)

D = effect of manure dilution (%)

E = effect of emitting area (cm^2).

The model contains linear terms and two-way interaction terms (block and round effect). Backward elimination was used to determine the interaction effects when running model 1, i.e., removing the interaction with the highest P-value at each iteration until all remaining interactions were significant ($P < 0.05$) or removed. A natural log (base e) transformation was applied to odor concentration, odor emission, the concentration of total and individual VFAs, total-N, NH_4^+ -N, and total-N loss, since they were skewed and non-normally distributed. The potential for multi-collinearity was evaluated by simple correlations among potential continuous explanatory variables. Additionally, basic descriptive statistics (mean, standard deviation, and range of dependent variables) were estimated.

RESULTS AND DISCUSSION

EFFECTS OF ENVIRONMENTAL FACTORS ON ODOR CONCENTRATION AND EMISSION

The net mean odor concentration, odor emission per hour, and odor emission per hour per square meter of the manure in the vessel were $1663 ou_E m^{-3}$, $99.40 ou_E h^{-1}$, $2326 ou_E h^{-1} m^{-2}$, respectively. They ranged from the lower detection limit of 224 to $6562 ou_E m^{-3}$, from 8.6 to $590.6 ou_E h^{-1}$, and from 263 to $19505 ou_E h^{-1} m^{-2}$, respectively (table 2). The mean odor concentration of the blank sample was $115 ou_E m^{-3}$. It ranged from 98 to $140 ou_E m^{-3}$. The gross odor concentration, odor emission per hour, and odor emission per hour per square meter were about 7% higher than the net concentration and emission rate. This implied that the incoming air was not totally free of odor. In practical situations, odor in the incoming air can supply a significant amount of the odor in the outgoing air, e.g., in a study by Lim et al. (2001), it was about 40%.

Table 2. Descriptive statistics of odor concentration and emission from pig manure ($n = 54$).

| Variables ^[a] | Mean | SD ^[b] | Min. - Max. |
|--|-------|-------------------|--------------|
| Net odor concentration ($ou_E m^{-3}$) | 1663 | 1337 | 224 - 6562 |
| ln(net odor concentration) | 7.15 | 0.76 | 5.41 - 8.79 |
| Net odor emission per hour ($ou_E h^{-1}$) | 93.4 | 88.3 | 8.60 - 590.6 |
| ln(net odor emission per hour) | 4.24 | 0.79 | 2.15 - 6.38 |
| Net odor emission per hour per square meter ($ou_E h^{-1} m^{-2}$) | 2326 | 2843 | 263 - 19505 |
| Odor concentration of blank samples ($ou_E m^{-3}$) ($n = 6$) | 115 | 17 | 98 - 140 |
| Gross odor concentration ($ou_E m^{-3}$) | 1779 | 1335 | 333 - 6672 |
| Gross odor emission per hour ($ou_E h^{-1}$) | 100.3 | 89.2 | 12.2 - 600.5 |
| Gross odor emission per hour per square meter ($ou_E h^{-1} m^{-2}$) | 2491 | 2885 | 318 - 19831 |

^[a] ln = natural logarithm.

^[b] SD = standard deviation.

The effect of environmental factors on both net and gross odor concentration and odor emission was analyzed. Because the trend and comparable magnitude of the estimated regression coefficient were found to be the same, the effect of environmental factors on net odor concentration and odor emission are presented in this article. All references to odor concentration and odor emission in this article imply the net values unless otherwise stated. The effect of environmental factors on odor emission per square meter was not analyzed because emitting area was one of the factors in the study. The odor emission in the regression analysis was odor emission per hour.

Temperature, ventilation rate, and manure dilution ratio influenced odor concentration and odor emission of the manure in the vessel ($P < 0.05$) (table 3), but emitting area and the two-way interaction terms of the four mentioned environmental factors did not ($P > 0.05$). As temperature and manure dilution ratio increased, odor concentration increased, but odor concentration decreased when ventilation rate increased. Odor emission from the manure in the vessel increased with temperature, ventilation rate, and manure dilution ratio. The models for odor concentration and odor emission with different environmental factors as independent factors accounted for 61.3% and 63.3% of the variation, respectively. The effects of temperature and ventilation rate on odor emission were much larger than those of manure dilution ratio and emitting area. Temperature and ventilation rate alone accounted for about 58.9% of the variance. When

adding emitting area and manure dilution ratio separately to the model, only 0.2% and 4.2% extra variance, respectively, was accounted for.

If other independent variables in the model were kept constant, both $\ln(C_{odor})$ and $\ln(E_t)$ increased about 0.058 units as temperature increased by 1 °C. When temperature increased from 10 °C to 30 °C, the estimated odor concentration and odor emission increased by 1726 $\text{ou}_E \text{ m}^{-3}$ and 90 $\text{ou}_E \text{ h}^{-1}$, respectively. This is equivalent to about 216%. Increasing the manure temperature increases the emissions and the bacterial biogenesis of odorous compounds. Higher temperatures stimulate the formation of ammonia (Bruns, 1997), hydrogen sulfide (Ni et al., 2000), 4-methyl phenol (p-cresol), and 3-methyl indole (skatole) (Spoelstra, 1976) in manure. Therefore, it was expected that increased temperature was associated with increased odor concentration and emission from the manure in the vessel. This finding was consistent with that of Mol and Ogink (2003), who found that cooling off the upper layer of the manure and the air-boundary layer in a manure pit could reduce odor concentration and emission from animal houses. It should be mentioned, however, that in our experiment the ventilation air and the manure temperature were the same. With manure cooling, only the temperature of the surrounding air and the top layer of the manure in the manure pit is influenced by the cooling system, not the deep layer of the manure in the manure pit and the rest of the air in pig houses. Cooling the upper layer of the manure proved to be an impor-

Table 3. Effects of environmental factors on odor concentration and emission and manure characteristics ($n = 54$)

| Response variables ^[a] | Estimated Regression Coefficients ^[b] | | | | | | | | | R ² ^[c] | RSD ^[d] |
|--|--|---------------------|--------------------------|------------------------|-----------------------|----------------------|-----------------------|-----------------------|--------------------|-------------------------------|--------------------|
| | Constant | T (°C) | V (L min ⁻¹) | E (cm ²) | D (%) | TV | TE | TD | ED | | |
| $\ln(\text{odor conc., } \text{ou}_E \text{ m}^{-3})$ | 6.65*** (0.36) | 0.058*** (0.008) | -0.42** (0.16) | -0.0007 (0.0005) | 0.004** (0.002) | -- ^[e] | -- | -- | -- | 61.3 | 0.47 |
| $\ln(\text{odor emission, } \text{ou}_E \text{ h}^{-1})$ | 2.60*** (0.37) | 0.058*** (0.008) | 0.68*** (0.16) | -0.0007 (0.0005) | 0.004** (0.002) | -- | -- | -- | -- | 63.3 | 0.48 |
| pH | 7.61*** (0.19) | 0.018* (0.008) | -0.11* (0.05) | 0.0005 (0.0004) | -0.004*** (0.0005) | -- | 44E-6** (17E-6) | -- | -- | 88.1 | 0.14 |
| $\ln(\text{total VFAs, g/kg ash})$ | 5.31*** (0.41) | 0.024 (0.018) | 0.43 (0.21) | 0.00005 (0.0007) | 0.001 (0.0009) | -0.03** (0.01) | -0.0001*** (33E-6) | -- | -- | 83.5 | 0.27 |
| $\ln(\text{acetic acid, g/kg ash})$ | 4.89*** (0.47) | 0.026 (0.021) | 0.41 (0.24) | -0.0003 (0.0008) | 0.002* (0.001) | -0.03** (0.01) | -0.0001** (37E-6) | -- | -- | 74.5 | 0.31 |
| $\ln(\text{propanoic acid, g/kg ash})$ | 4.96*** (0.68) | -0.043 (0.025) | 1.01 (0.57) | -0.0028*** (0.0007) | -0.006** (0.002) | -0.09*** (0.023) | -- | -- | -- | 79.7 | 0.65 |
| $\ln(\text{butanoic acid, g/kg ash})$ | 4.06*** (1.01) | -0.075 (0.044) | -0.127 (0.25) | 0.0023 (0.0019) | -0.008 (0.006) | -- | -0.0003** (89E-6) | 0.0006* (0.0002) | -- | 82.3 | 0.73 |
| $\ln(\text{pentanoic acid, g/kg ash})$ | 1.93** (0.65) | -0.08*** (0.03) | -0.067 (0.15) | 0.0003 (0.0012) | -0.008* (0.004) | -- | -0.0002** (54E-6) | 0.0006*** (0.0001) | -- | 85.1 | 0.45 |
| $\ln(\text{iso-butanoic acid, g/kg ash})$ | 1.21* (0.56) | 0.054* (0.023) | 0.36 (0.27) | 0.003** (0.001) | 0.01*** (0.003) | -0.03** (0.01) | -0.0002*** (42E-6) | -- | -23E-6** (8E-6) | 81.6 | 0.35 |
| $\ln(\text{iso-pentanoic acid, g/kg ash})$ | 2.46*** (0.41) | 0.017 (0.017) | 0.39* (0.20) | 0.002** (0.0007) | -0.001 (0.003) | -0.031*** (0.009) | -0.0002*** (30E-6) | 0.004*** (88E-6) | -13E-6* (6E-6) | 89.3 | 0.25 |
| $\ln(\text{total-N, g/kg ash})$ | 5.33*** (0.04) | -0.005** (0.001) | 0.031 (0.030) | -0.0001** (44E-6) | -0.0001 (0.0003) | -0.007*** (0.001) | -- | 62E-6*** (13E-6) | -- | 88.4 | 0.04 |
| $\ln(\text{NH}_4^+\text{-N, g/kg ash})$ | 4.99*** (0.79) | -0.01*** (0.003) | 0.02 (0.05) | 0.0001* (72E-6) | -0.0002 (0.0005) | -0.009*** (0.002) | -- | 0.0001*** (22E-6) | -- | 87.4 | 0.06 |
| $\ln(\text{total-N loss, g/vessel})$ | -2.51*** (0.18) | 0.06*** (0.004) | 0.68*** (0.08) | 0.0009** (0.0003) | -0.007*** (0.0008) | -- | -- | -- | -- | 87.7 | 0.24 |

[a] \ln = natural logarithm.

[b] * = $p < 0.05$, ** = $p < 0.01$, and *** = $p < 0.001$; values in parentheses are standard errors.

[c] R² = percentage variance accounted for.

[d] RSD = residual standard deviation.

[e] -- = dropped from the model by backward elimination because of its non-significant effect.

tant principle to reduce ammonia emission from pig houses. Our findings show that manure temperature has a big influence on both ammonia and odor emissions. A lower temperature gives lower emissions by slowing odor formation and odor release from the manure. On the other hand, a higher temperature stimulates the breakdown of odorous compounds to end products such as methane and carbon dioxide. However, as discussed by Pain and Bonazzi (1993), this is a far slower process than the formation process.

If other independent variables were kept constant, $\ln(C_{odor})$ was reduced by 0.42 ($P < 0.05$) as the ventilation rate increased from 0.5 to 1.5 L min⁻¹. However, in that case, $\ln(E_t)$ increased by 0.68. When the ventilation rate increased from 0.5 to 1.5 L min⁻¹, the estimated odor concentration decreased by 600 ou_E m⁻³ (34%) and the estimated odor emission increased by 52 ou_E h⁻¹ (97%). An increased ventilation rate provides higher dilution of odorous compounds with fresh air and so reduces odor concentration. Odor emission, however, is increased because of higher partial pressures between odorous compounds in the manure and in the air. The positive relationship between ventilation rate and odor emission found in this study was consistent with that of Oldenburg (1989) and Verdoes and Ogink (1997). In our study, ventilation rate was independent of temperature. This was normally not the case in previous studies, where the effect of ventilation rate on odor emission was more or less confounded with that of temperature and animal mass.

Increased manure dilution ratio was associated with increased odor concentration and odor emission ($P < 0.05$). When the manure dilution ratio increased from 0% to 100%, the estimated odor concentration and odor emission increased by 563 ou_E m⁻³ and 30 ou_E h⁻¹, respectively. This is equivalent to about 50%. The reason is probably that increased manure dilution reduced pH ($P < 0.05$) (table 3). When the manure dilution ratio increased from 0% to 100%, the estimated pH decreased by 0.4, which might create favorable conditions for the emission of odorous compounds such as VFAs. The other reason is that increased manure dilution ratio favored the dilution of odorous compounds from organic materials into liquid. Therefore, odorous compounds were more easily exchanged to the air. In addition, one might expect that the effect of manure dilution ratio on odor concentration and emission was partly confounded with that of headspace volume. Because the vessels had different surfaces but the same height (23.5 cm), they were different in the total volume and thus different in headspace volume. The total volumes of the vessels with 303, 475, and 595 cm² surfaces were 7116, 11164, and 13991 cm³, respectively. Although, no significant effects of the interaction between dilution ratio and headspace volume on odor concentration and emission ($P > 0.05$) were found, and the correlation between dilution ratio and headspace volume was quite low ($r = -0.28$), the confounding effects of dilution ratio and headspace volume could not be fully excluded.

Emitting area did not significantly influence odor concentration and emission ($P > 0.05$). Our finding was not consistent with those of Mol and Ogink (2003) and Ogink and Groot Koerkamp (2001). When measuring odor emission from manure pits at a certain point of time, they reported that reducing emitting area could reduce odor emission. There are three possible explanations for this inconsistency. First, most odorous compounds are less soluble in water than ammonia.

They are quickly emitted to the air after being produced in the manure. As a result, emitting area was expected to have a significant effect on nitrogen loss (mainly in the form of ammonia) but not on less soluble odorous compounds. This can be confirmed by the significant effect ($P < 0.05$) of emitting area on total-N concentration in manure after the experiment, and on total-N loss (table 3). Second, in our experiment, odor samples were collected from exactly the same amount of manure in all treatments. In the previous studies, the emitting area was probably confounded with the amount of manure. The system with a small emitting area generally had manure pits with less manure, and the manure was more often removed from the pig house. Third, the effect of emitting area on odor concentration and emission might be partly confounded with that of headspace volume. Actually, the two factors are highly correlated ($r = 0.96$).

The effects of emitting area and manure dilution ratio could not be fully separated from the effect of headspace volume in this study. The changes in headspace volume were due to adding dilution water and changing emitting area. In practice, similar confounding happens. Manure pits have different emitting areas and are recharged with different amount of manure and water. This creates different headspace volumes. Headspace volume might affect the air velocity above the emitting area, and thereby influence odor emission.

However, when adding headspace volume to the model that already contained temperature and ventilation rate, the effect of headspace volume was not significant. In addition, it is worth mentioning that adding headspace volume to the model that already contained emitting area (fitted terms: T, V, E, and HSV) or manure dilution ratio (fitted terms: T, V, D, and HSV) did not change the percentage of variance accounted for in model 1 (fitted terms: T, V, D, and E). All had the same percentage of variance and accounted for 63.3% of odor emission variance. From the preceding discussion, we conclude that headspace volume in our study had very little effect on odor emission from the manure vessel.

EFFECTS OF ENVIRONMENTAL FACTORS ON N LOSSES AND MANURE CHARACTERISTICS

Table 4 presents manure characteristics before and after the experiment. These include pH, dry matter, ash, VFAs, ammonium, total-N, and total-N loss. Means and standard deviations (in parentheses) are presented to give a range of expected values of manure characteristics. The concentrations of individual VFAs, total VFAs, ammonium, total-N, and dry matter were calculated per kg of manure and per kg of ash. The latter excludes the effect of dilution of the manure with water. After seven days of running the experiment, the total VFA concentration per kg of ash was reduced by 69%, individual VFA concentrations per kg of ash was reduced in the range from 50% (iso-butyric acid) to 85% (propanoic acid), ammonium and total-N concentrations per kg of ash were reduced by 19% and 13%, respectively, and pH increased by 0.76.

The pH of manure after the experiment can be explained in relationship with the ammonium and total VFA concentrations (both in g kg⁻¹) in the manure. The regression model is given in equation 6 (values in parentheses are standard errors):

Table 4. Descriptive statistics of manure characteristics before dilution of the manure and after the experiment.

| Variables | Before Dilution (n = 4) | | After Experiment (n = 54) | | Percent Change per kg Ash |
|---|---|-----------------------|---------------------------|-----------------------|---------------------------|
| | Per kg Manure, Mean (SD) ^[a] | Per kg Ash, Mean (SD) | Per kg Manure, Mean (SD) | Per kg Ash, Mean (SD) | |
| Dry matter (g kg ⁻¹) | 34.72 (0.73) | 2408 (49) | 24.5 (7.4) | 2244 (93) | -7 |
| Ash (g kg ⁻¹) | 14.42 (0.07) | -- ^[b] | 11.0 (3.4) | -- | -- |
| Total VFAs (g kg ⁻¹) ^[c] | 6.06 (0.15) | 420 (10) | 1.37 (0.87) | 128.4 (72.1) | -69 |
| Acetic acid (g kg ⁻¹) | 4.11 (0.14) | 285 (9) | 0.97 (0.53) | 92.1 (47.4) | -68 |
| Propanoic acid (g kg ⁻¹) | 1.09 (0.02) | 75.4 (1.6) | 0.13 (0.15) | 11.65 (11.97) | -85 |
| Butanoic acid (g kg ⁻¹) | 0.32 (0.02) | 22.2 (1.8) | 0.07 (0.07) | 6.74 (6.14) | -70 |
| Pentanoic acid (g kg ⁻¹) | 0.048 (0.004) | 3.30 (0.27) | 0.010 (0.009) | 0.92 (0.75) | -72 |
| Iso-butanoic acid (g kg ⁻¹) | 0.193 (0.004) | 13.42 (0.32) | 0.07 (0.05) | 6.70 (3.91) | -50 |
| Iso-pentanoic acid (g kg ⁻¹) | 0.302 (0.006) | 20.98 (0.46) | 0.11 (0.09) | 10.37 (6.27) | -51 |
| Total-N (g kg ⁻¹) | 2.78 (0.01) | 193.1 (1.6) | 1.81 (0.49) | 167.8 (17.4) | -13 |
| NH ₄ ⁺ -N (g kg ⁻¹) | 1.89 (0.02) | 131.6 (1.1) | 1.14 (0.31) | 106.3 (16.4) | -19 |
| pH | 7.49 (0.06) | -- | 8.25 (0.41) | -- | -- |

[a] SD = standard deviation.

[b] -- = not applicable.

[c] Total VFAs = acetic acid + propanoic acid + butanoic acid + pentanoic acid + iso-butanoic acid + iso-pentanoic acid.

$$\text{pH} = 7.88(0.15) + 0.932(0.16) \text{ ammonium} \\ - 0.50(0.06) \text{ totalVFAs} \quad R^2 = 61\% \quad (6)$$

The model explained 61% of the variance in pH. Our study confirmed the results of Sommer and Husted (1995), Aarnink et al. (1996), and Canh et al. (1998a), who stated that pH of the manure is mainly affected by concentrations of ammonium and total VFAs.

The VFA pool was largely dominated by short straight-chain VFAs (acetic, propanoic, and butanoic acids), which comprised 91% and 86% of total VFAs in the manure before and after the experiment, respectively. This confirms the results of Miller and Varel (2003) and Otto et al. (2003). Acetic acid was the main VFA contributing to total VFAs in the manure (68% and 70.6%, respectively, before and after the experiment), confirming the results of Canh et al. (1998b) and Farnworth et al. (1995). Short branched-chain VFAs contributed minimally to the total VFA concentration in the manure.

Dry matter of the manure before the experiment was 34.7 g kg⁻¹. This is a rather low concentration when compared to other studies, e.g., Bakker et al. (2004), in which it was about 80 g kg⁻¹. There are two possible reasons for this observation. First, pigs may have played with the water drinker, resulting in water spillage on the floor and then into the manure pit. Second, manure was collected from the manure pit, which had not been emptied for two months, and conversions within the manure during storage could reduce its dry matter.

Table 3 presents the effect of environmental factors on total-N loss and manure characteristics during the experiment. The concentrations of total-N, ammonium-N, total VFAs, and individual VFAs were calculated per kg ash. Temperature influenced the concentrations of total-N, ammonium-N, total-N loss, and pH ($P < 0.01$), but not the concentrations of total VFAs and individual VFAs ($P > 0.05$), except for pentanoic and iso-butanoic acids. When other independent factors were kept constant, total-N concentration decreased by 0.5% and total-N loss increased by 6% for each increase of 1 °C. Ventilation rate had no significant effect on total VFA concentration, but a positive effect on total-N loss and a negative effect on pH ($P < 0.05$). When the

other factors are kept constant, estimated total-N loss increased by 97.4% as ventilation rate increased from 0.5 to 1.5 L min⁻¹. Emitting area did not influence odor concentration, odor emission, total VFA concentration, and pH ($P > 0.05$). However, total-N concentration was reduced by 0.01% and total-N loss was increased by 0.09% ($P < 0.05$) as emitting area increased by 1 cm². This was expected because ammonia is soluble in water, and therefore its loss depends on emitting area. Increased dilution rate was associated with reduced total-N loss. Total-N loss decreased by 0.7% with each 1% increase in manure dilution. Manure dilution reduces ammonia concentration in the manure. According to Aarnink and Elzing (1998), ammonia emission is linearly related to ammonia concentration. Furthermore, manure dilution caused a lowering of the pH of the manure. A lower pH reduces ammonia volatilization as well (Aarnink, 1997; Sommer and Husted, 1995). The effects of two-way interactions of the environmental factors on manure characteristics were not consistent and are difficult to explain.

CONCLUSIONS

From the study on the effect of temperature, ventilation rate, emitting area, and manure dilution ratio on odor emission from manure and manure characteristics in a laboratory setup, we conclude the following:

- Increasing the temperature and the dilution ratio of the manure increased the odor concentration. When temperature increased from 10 °C to 30 °C and the manure dilution ratio increased from 0% to 100%, the odor concentration increased by 216% and 50%, respectively.
- Increasing the temperature and the dilution ratio of the manure increased the odor emission. When the temperature increased from 10 °C to 30 °C and the manure dilution ratio increased from 0% to 100%, the odor emission increased by 216% and 50%, respectively.
- Increasing the ventilation rate of the manure vessel reduced the odor concentration, but increased the odor emission. When the ventilation rate increased from 0.5 to 1.5 L min⁻¹, odor concentration decreased by 34% and odor emission increased by 97%.
- The emitting area of the manure surface did not influence odor concentration and emission.

- After running the experiment for seven days, total VFA concentration decreased by 69%, total-N and ammonium concentrations decreased by 13% and 19%, respectively, and pH of the manure increased by 0.76.
- Total-N loss increased with temperature (6% per °C), with ventilation rate (an increase of 97.4% as ventilation increased from 0.5 to 1.5 L min⁻¹), and with emitting area (0.09% for each cm² larger area), but decreased with manure dilution ratio (0.7% for each 1% manure dilution).
- Temperature, ventilation rate, manure dilution ratio, and emitting area did not influence VFA concentration.
- Increased ventilation rate and manure dilution ratio lowered the pH of the manure, but higher temperature increased the pH.
- Effects of manure dilution ratio and emitting area on odor emission and manure characteristics were partly confounded with headspace volume.

The results from this study confirmed the hypothesis that odor emission from pig manure can be reduced by altering environmental factors. Lowering the temperature and ventilation rate can be considered as possible measures to reduce odor emission from pig manure. We suggest that further studies on the effect of manure dilution ratio and emitting area on odor emission are required.

ACKNOWLEDGEMENTS

We acknowledge the financial support from the Dutch Ministry of Agriculture, Environment, and Food quality.

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